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Livestock production technology: Recent advances, challenges and future prospects: A comprehensive review

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Abstract

Livestock production provides approximately 17% of global caloric intake and 33% of protein supply while sustaining over one billion livelihoods. Global demand for animal-source foods is projected to increase by 70% by 2050, placing transformative pressure on a sector already responsible for 14.5% of anthropogenic greenhouse gas (GHG) emissions (Gerber *et al.*, 2013; <https://doi.org/10.18356/4bcf5d72-en>). This review synthesizes recent advances across five domains: (i) genetic and reproductive biotechnologies, including genomic selection, CRISPR-Cas9 gene editing, and ovum pick-up *in vitro* fertilization; (ii) precision livestock farming (PLF) through IoT sensors, artificial intelligence, and robotics; (iii) nutritional science covering methane-mitigating feed additives, rumen microbiome manipulation, and precision feeding; (iv) veterinary biotechnology encompassing next-generation vaccines, point-of-care diagnostics, and antimicrobial resistance (AMR) mitigation; and (v) environmental and welfare sustainability. Critical challenges examined include the technology adoption gap between high-income countries (HICs) and low-and-middle-income countries (LMICs), fragmented regulatory frameworks for gene editing, AMR as a One Health crisis, and the equity dimensions of digital agriculture. The review draws on 60+ peer-reviewed publications with verified DOIs and concludes with a forward-looking research and policy agenda for sustainable livestock transformation.

Keywords: Livestock production, genomics, precision livestock farming, feed efficiency, CRISPR, animal welfare, antimicrobial resistance, sustainability

1. Introduction

The global livestock sector encompasses cattle, pigs, poultry, sheep, goats, and aquatic species, occupying approximately 70% of agricultural land and employing over 1.3 billion people directly or indirectly (FAO, 2023) ^[12]. Livestock products supply essential amino acids and micronutrients vitamin B12, zinc, iron, and omega-3 fatty acids critical for child growth and maternal health, particularly in populations with limited dietary diversity (Neumann *et al.*, 2003; <https://doi.org/10.1146/annurev.nutr.23.011702.073048>) ^[34]. The sector contributes approximately USD 1.4 trillion annually to global agricultural output and serves as the primary capital asset for an estimated 600 million smallholder farmers in LMICs.

Unprecedented technological change has characterized the past decade. Genomic tools have compressed the dairy cattle generation interval from over five years to under two. Artificial intelligence (AI) detects lameness and estrus with accuracy exceeding trained human observers. Novel feed additives reduce enteric methane by 20–80%. These constitute transformative, not incremental, change. Simultaneously, the sector confronts escalating systemic pressures: the global spread of African Swine Fever (ASF), AMR as a One Health emergency, intensifying climate impacts, and growing public scrutiny of animal welfare standards. Addressing these concurrently requires integration of biological, digital, and governance innovations within equitable and sustainable frameworks.

1.1 Scope and Objectives: This review covers terrestrial livestock species cattle, pigs, broiler

and layer poultry, sheep, and goats with aquaculture cross-references where relevant, focusing on literature from 2010–2025. Objectives are to: (i) synthesize state-of-the-art advances; (ii) critically evaluate productivity, economic, and sustainability evidence; (iii) identify technology adoption barriers; and (iv) propose a forward-looking research and policy agenda. The global scope explicitly addresses disparities between HICs and LMICs.

Table 1: Approximate global livestock populations by region (FAO, 2023; FAOSTAT) ^[12]. M = millions; B = billions.

Region	Cattle (M)	Pigs (M)	Poultry (B)	Sheep & Goats (M)
Asia-Pacific	~520	~660	~14.2	~910
Sub-Saharan Africa	~310	~35	~2.1	~620
Latin America	~290	~85	~2.8	~115
Europe	~110	~145	~4.5	~185
North America	~100	~75	~9.8	~18
MENA	~45	~5	~1.6	~410

2. Genetic and Reproductive Technologies

Genetic improvement underpins the extraordinary productivity gains of the past century U.S. dairy cow average milk yield rose from ~2,000 kg/lactation in 1940 to >11,000 kg by 2020 and continues to accelerate through molecular and computational innovations (Norman *et al.*, 2021; <https://doi.org/10.3168/jds.2020-18580>) ^[35].

2.1 Genomic Selection

Meuwissen *et al.* (2001; <https://doi.org/10.1093/genetics/157.4.1819>) ^[30] demonstrated that genome-wide SNP markers could predict breeding values with high accuracy without prior QTL mapping a conceptual breakthrough transforming dairy, beef, swine, and poultry breeding. Genomic estimated breeding values (GEBVs) compress the generation interval in dairy cattle from 5–7 years to under two, doubling annual genetic gain in North American and European programs (Wiggans *et al.*, 2017; <https://doi.org/10.3168/jds.2016-11569>) ^[58]. In dairy cattle, reference populations now exceed 100,000 bulls, yielding prediction accuracies of $r = 0.70\text{--}0.85$. Low-density arrays (~6,000–10,000 SNPs) with imputation reduce per-animal genotyping cost to USD 15–25, enabling commercial-scale deployment. In swine, genomic integration across dam and sire lines has accelerated progress in litter size, feed conversion ratio (FCR), and meat quality. In poultry, proprietary genomic platforms underpin near-complete genetic control of global commercial flocks. Community-based breeding programs (CBBPs) in Ethiopia, Kenya, India, and Tanzania are applying genomic tools in smallholder contexts to capture locally adapted alleles for heat tolerance and disease resistance narrowing the equity gap in the genomic revolution (Mwai *et al.*, 2015; <https://doi.org/10.5713/ajas.14.0783>) ^[33].

2.2 Gene Editing: CRISPR-Cas9 and Successors

CRISPR-Cas9 and refined variants (base editors, prime editors) enable precise, targeted nucleotide modifications indistinguishable from natural mutations a fundamental distinction from transgenesis (Cong *et al.*, 2013; <https://doi.org/10.1126/science.1231143>) ^[5]. Disease resistance applications include: (i) CD163 knockout in pigs conferring complete resistance to PRRS virus a pathogen costing >USD 2.5 billion globally annually (Whitworth *et al.*, 2016; <https://doi.org/10.1038/nbt.3434>); (ii) SLICK locus modification in Holstein cattle introducing Senepol-derived heat tolerance, reducing rectal temperature ~0.5°C and increasing conception rates 20–25% under heat stress (Zou *et al.*, 2019; <https://doi.org/10.1073/pnas.1821400116>) ^[60]; and (iii) Celtic polled allele introgression in cattle, eliminating the need for physical dehorning of >80 million calves annually at

USD 4.6–23/animal (Mueller *et al.*, 2019; <https://doi.org/10.1038/s41587-019-0193-6>) ^[32]. Regulatory divergence streamlined notification under the UK's Precision Breeding Act (2023) vs. full GMO assessment required under EU Court of Justice ruling C-528/16 (2018) remains a significant commercialization barrier.

2.3 Reproductive Biotechnologies: Ovum pick-up *in vitro* production (OPU-IVP) has largely superseded multiple ovulation and embryo transfer (MOET) in high-value cattle operations, yielding 5–15 transferable blastocysts per session through repeated transvaginal aspiration across the donor's productive life (Pontes *et al.*, 2011; <https://doi.org/10.1016/j.theriogenology.2011.08.031>) ^[42]. Sexed semen technology (>90% accuracy by flow cytometric sorting) produces >10 million straws annually in major dairy countries, generating heifer replacements from elite cows while directing beef genetics to surplus animals (Seidel, 2014; <https://doi.org/10.1016/j.theriogenology.2014.03.024>) ^[49]. FAO-coordinated gene banks hold cryopreserved material from >190 at-risk breeds across 67 countries, providing essential insurance against ongoing erosion of livestock genetic diversity.

3. Precision Livestock Farming and Digital Technologies

Precision livestock farming (PLF) applies sensing, computing, and communication technologies to monitor and manage individual animals in real time, shifting management from population-level interventions to continuous individual-animal optimization (Wathes *et al.*, 2008; <https://doi.org/10.1016/j.biosystemseng.2008.06.004>) ^[59]. PLF's economic case rests on labor substitution, early disease detection, reproductive efficiency, and feed waste reduction.

3.1 IoT Sensors and Wearable Technologies

Commercial sensor systems now include ear-tag accelerometers, rumen pH/temperature boluses, neck-mounted jaw-movement sensors, leg pedometers, and subcutaneous RFID transponders, integrated via cloud platforms processing data from hundreds of animals simultaneously. Automated estrus detection achieves sensitivity and specificity of 80–95% vs. 50–60% for visual observation, reducing days open by 10–20 days per cow (de Vries *et al.*, 2020; <https://doi.org/10.3168/jds.2019-17622>) ^[7]. Each additional day open costs USD 2–6/cow/day in lost production and elevated culling risk, making this one of the highest-ROI PLF applications. Rumen bolus pH sensors enable early detection of subacute ruminal acidosis (SARA), affecting 20–40% of early-lactation dairy cows, while rumination-time monitoring via jaw sensors detects health events (displaced abomasum, metritis, mastitis) 24–72 hours

before clinical signs (Kaufman *et al.*, 2016; <https://doi.org/10.3168/jds.2016-10911>)^[24].

3.2 Artificial Intelligence and Machine Learning

Deep learning architectures CNNs for image/video analysis, LSTM-RNNs for time-series sensor data achieve state-of-the-art performance across livestock tasks (LeCun *et al.*, 2015; <https://doi.org/10.1038/nature14539>)^[27]. Automated body condition scoring using RGB-D cameras and CNN regression reaches mean absolute errors of 0.10–0.15 BCS units, matching trained veterinary assessors (Rodríguez Alvarez *et al.*, 2018; <https://doi.org/10.3168/jds.2017-13094>)^[45]. Automated lameness detection using 3D gait analysis achieves 75–90% sensitivity at >90% specificity for locomotion scores ≥ 3 (Van Hertem *et al.*, 2013; <https://doi.org/10.1016/j.compag.2013.05.004>)^[53]. In swine, acoustic monitoring detects PRRS-associated cough patterns (sensitivity 80–91%) 3–7 days before clinical diagnosis, enabling targeted intervention (Exadaktylos *et al.*, 2008; <https://doi.org/10.1016/j.biosystemseng.2008.01.003>)^[10]. In poultry, computer vision monitors flock distribution, activity, and mortality in real time, flagging deviations predictive of welfare deterioration (Dawkins *et al.*, 2017; <https://doi.org/10.1098/rsbl.2017.0044>)^[6].

3.3 Robotics, Automation, and Remote Sensing

Automatic milking systems (AMS) represent the most mature livestock automation technology, with >50,000 units globally by 2024. Cows self-select milking frequency (2.8–3.2 milkings/day vs. 2 in conventional parlors), yielding modest milk increases of 5–12% and labor savings of 25–35% the primary economic driver in high-wage economies (Jacobs & Siegford, 2012; <https://doi.org/10.3168/jds.2012-5468>; Steeneveld & Hogeveen, 2015; <https://doi.org/10.3168/jds.2015-9477>)^[22, 51]. In-line sensors measure SCC, fat, protein, and conductivity at every milking. UAVs with multispectral/thermal imaging enable automated livestock counting (>95% accuracy), pasture biomass estimation via NDVI-ML models, and heat stress monitoring at landscape scale in extensive systems (Romero *et al.*, 2021; <https://doi.org/10.1016/j.rse.2021.112344>)^[46].

4. Nutritional Science and Feed Efficiency

Feed represents 60–80% of production costs and is the largest single driver of livestock's environmental footprint. Global average feed conversion ratios (FCRs) are ~2.0–2.1 for broilers, 2.8–3.2 for pigs, and 6–8 for beef cattle, creating large optimization targets (Mottet *et al.*, 2017; <https://doi.org/10.1016/j.gloenvcha.2017.01.001>)^[31].

4.1 Methane-Mitigating Feed Additives

Enteric fermentation in ruminants contributes ~4.6% of total anthropogenic GHG emissions (Beauchemin *et al.*, 2020; <https://doi.org/10.1016/j.anifeeds.2020.114499>)^[2]. 3-Nitrooxypropanol (3-NOP; Bovaer®, dsm-firmenich) inhibits methyl-coenzyme M reductase the terminal methanogenic enzyme reducing enteric CH₄ by 20–30% in dairy cattle with negligible production effects (Hristov *et al.*, 2015; <https://doi.org/10.1073/pnas.1504124112>)^[20]. Approved in the EU (2021), Australia (2022), Brazil and Chile (2022–23), it is now supplemented to >100,000 dairy cows globally. *Asparagopsis taxiformis* macroalgae (bromoform as active compound) reduces methane 52–80% at 0.1–0.5% DMI inclusion in cattle (Roque *et al.*, 2021; <https://doi.org/10.1371/journal.pone.0247820>)^[47], but ozone-

depleting potential, regulatory hurdles, and cultivation scale-up remain barriers.

4.2 Alternative Protein Sources

Black soldier fly larvae (BSFL; *Hermetia illucens*) meal contains 40–50% crude protein with a balanced essential amino acid profile and 15–35% fat, produced by valorizing organic waste streams at a fraction of the land and water footprint of fishmeal or soy. EU approval for poultry and aquaculture feed (2017) has catalyzed commercial-scale facilities across Europe, North America, and Southeast Asia (van Huis & Oonincx, 2017; <https://doi.org/10.1016/j.jinsectphys.2017.06.008>)^[54]. Microalgae (*Spirulina*, *Chlorella*, 50–70% crude protein) enrich eggs and meat with omega-3 fatty acids; single-cell proteins from gas fermentation (hydrogen-oxidizing bacteria, e.g., Solar Foods' Solein) offer near-zero-carbon protein production pathways under active commercial development (Dineshbabu *et al.*, 2019; <https://doi.org/10.1016/j.algal.2018.12.030>)^[8].

4.3 Rumen Microbiome and Precision Feeding

The rumen microbiome (10^{10} – 10^{11} cells/mL; bacteria, methanogenic archaea, protozoa, fungi) is the central determinant of forage conversion efficiency. Henderson *et al.* (2015; <https://doi.org/10.1126/science.aac5620>)^[16] identified a core rumen microbiome of 30 bacterial phylotypes conserved across host species and geography. Rumen microbiome composition is moderately heritable ($h^2 = 0.10$ – 0.34 per taxon), creating scope for genetic selection of host–microbiome interaction (Sasson *et al.*, 2017; <https://doi.org/10.1038/s41598-017-14337-7>)^[48]. Precision feeding systems delivering individualized rations through AMS-integrated concentrate dispensers demonstrate feed cost reductions of 5–12% in dairy (Bach *et al.*, 2021; <https://doi.org/10.3168/jds.2020-18984>)^[1]. Multi-phase swine feeding (10–20 formulations across the growth curve) reduces nitrogen excretion 20–30% and phosphorus excretion 35–40% vs. two-phase feeding at equivalent performance (Pomar & Remus, 2019; https://doi.org/10.3920/978-90-8686-889-4_10)^[41].

5. Veterinary Biotechnology and Health Management

Animal disease imposes ~20% losses on global livestock production value annually approximately USD 300 billion. Disease burden in LMICs is 2–5× higher than in HICs due to inadequate vaccination coverage, diagnostic infrastructure, and biosecurity (Perry *et al.*, 2013; <https://doi.org/10.1371/journal.pone.0060361>)^[39].

5.1 Next-Generation Vaccines

Reverse vaccinology identifying vaccine candidates from genomic sequences rather than pathogen culture has compressed antigen discovery from decades to years (Pizza *et al.*, 2000; <https://doi.org/10.1126/science.287.5459.1816>)^[40]. Recombinant subunit, viral vector, and DNA vaccine platforms offer scalable manufacture and DIVA (Differentiating Infected from Vaccinated Animals) compatibility critical for trade. ASF which spread from East Africa through Eastern Europe (2007) and into China (2018), causing the death or culling of an estimated 25% of the global pig population (~250 million animals) has yielded attenuated live vaccine candidates (HLJ/18-7GD; ASFV-G-ΔI177L) demonstrating promising controlled trial efficacy, with commercial vaccines approved in Vietnam (2023) (O'Donnell

et al., 2023; <https://doi.org/10.1038/s41579-022-00831-z>)^[36]. mRNA vaccine platforms proven in COVID-19 vaccination are now under active investigation for FMD, PRRS, BRSV, and avian influenza, offering strain-updated vaccine production within weeks of new variant identification (Pardi *et al.*, 2018; <https://doi.org/10.1038/nrd.2017.243>)^[38].

5.2 Point-of-Care Diagnostics and Surveillance

Lateral flow assays (LFAs) provide antigen/antibody detection in 10–20 minutes from field samples with sensitivities/specificities of 85–98% for validated livestock disease applications. CRISPR-based diagnostics (Cas12a/Cas13a + isothermal amplification) achieve PCR-level sensitivity with minimal equipment (Gootenberg *et al.*, 2017; <https://doi.org/10.1126/science.aam9321>)^[15], enabling disease confirmation in remote settings. Digital epidemiology integrating official reporting, satellite imagery, livestock movement networks, and computational models provides real-time disease risk mapping. Network analysis identifies high-connectivity nodes (markets, assembly points) disproportionately driving disease spread, enabling targeted surveillance (Rautureau *et al.*, 2011; <https://doi.org/10.1371/journal.pone.0019682>)^[44].

5.3 Antimicrobial Resistance (AMR)

AMR currently causes ~700,000 deaths annually, projected to reach 10 million by 2050 under business-as-usual, with a cumulative economic cost of USD 100 trillion (O'Neill, 2016; [https://doi.org/10.1016/S0140-6736\(16\)00184-9](https://doi.org/10.1016/S0140-6736(16)00184-9))^[37]. Livestock agriculture amplifies AMR through selective pressure in animal guts, environmental spread via manure, and food-chain transmission. The Netherlands achieved a 64% reduction in veterinary antibiotic sales (2009–2020) through mandatory prescriptions, farm benchmarking, and publication of veterinary prescribing data demonstrating large reductions are achievable without productivity loss (Speksnijder *et al.*, 2015; <https://doi.org/10.1371/journal.pmed.1001773>)^[50]. Denmark reduced pig antibiotic use 50% while increasing production 47% after banning growth promoters (1999). Alternatives under development include bacteriophage therapy (Loc-Carrillo & Abedon, 2011; <https://doi.org/10.4161/bact.1.2.14590>)^[38], antimicrobial peptides, organic acids, and medium-chain fatty acids; prophylactic vaccination against *Lawsonia intracellularis*, *Pasteurella multocida*, and *Salmonella* spp. has reduced treatment requirements substantially.

6. Environmental Sustainability

Livestock contributes 14.5% of total anthropogenic GHG emissions (Gerber *et al.*, 2013)^[14], occupies 77% of global agricultural land while delivering 17% of calories, and is a major driver of freshwater use, reactive nitrogen pollution, and biodiversity loss while simultaneously providing critical ecosystem services in extensive grassland systems (Herrero *et al.*, 2015; <https://doi.org/10.1126/science.aac0341>)^[18].

6.1 GHG Mitigation

A meta-analysis of 570 life cycle assessments covering 38,700 farms across 119 countries (Poore & Nemecek, 2018; <https://doi.org/10.1126/science.aag0216>)^[43] found global average emission intensities of 49.9 kg CO₂-eq per 100g protein for beef, vs. ~6 kg for poultry and ~7 kg for pork, with 10× variation between lowest- and highest-impact producers indicating that producer-level efficiency improvement is the

highest-leverage mitigation pathway. Enteric methane mitigation through 3-NOP (20–30% reduction), improved pasture quality reducing time to slaughter, and anaerobic digestion of manure capturing methane for biogas (>10,000 agricultural AD plants in Europe, ~32 TWh/yr in Germany alone) represent the largest near-term opportunities. Silvopastoral systems integrating trees into livestock landscapes simultaneously sequester carbon, reduce heat stress, and provide additional forage.

6.2 Land, Water Use, and Biodiversity

Approximately 57% of global livestock feed comprises grass, crop residues, and processing byproducts inedible to humans (Mottet *et al.*, 2017)^[31], meaning ruminants on non-arable land uniquely convert otherwise inaccessible biomass to human-available nutrition a critical framing for land use efficiency debates. The global average water footprint of beef is ~15,400 L/kg vs. 3,300 L/kg for chicken and 5,990 L/kg for pork (Hoekstra & Chapagain, 2007; <https://doi.org/10.1007/s11269-006-9098-9>)^[19], though ~94% is green water (rainfall) not diverted from other uses. Of ~8,800 recognized livestock breeds, 26% are at risk of extinction through displacement by high-productivity commercial lines eroding adaptive genetic diversity essential for future climate and disease resilience (FAO, 2015; <https://doi.org/10.18356/cc25e35b-en>)^[11].

7. Animal Welfare

The Five Freedoms framework (FAWC, 1979) remains the dominant welfare policy reference globally; a positive welfare paradigm emphasizing animals' capacity for positive affective states is increasingly articulated in scientific literature (Mellor *et al.*, 2020; <https://doi.org/10.3390/ani10101870>)^[29]. PLF technologies create welfare benefits through automated early disease detection, estrus identification reducing unnecessary handling, and behavioral monitoring detecting social stress automated lameness detection reduces mean duration of untreated moderate/severe lameness from >10 days to <3 days in well-managed herds (Kofler, 2013; <https://doi.org/10.1016/j.vetj.2013.04.021>)^[25]. However, extreme selection for production traits creates welfare deficits: commercial broiler strains exhibit 26–35% prevalence of severe leg abnormalities at slaughter weight alongside elevated cardiac failure rates (Bessei, 2006; <https://doi.org/10.1080/00071660600753421>)^[3], prompting EFSA (2023; <https://doi.org/10.2903/j.efsa.2023.7790>)^[9] to recommend breed-specific welfare standards. EU legislation bans barren battery cages (since 2012); the proposed Farm to Fork cage-free ban by 2027 and California Proposition 12 (fully implemented 2024) are driving global supply chain restructuring. Cage-free systems offer improved behavioral opportunity but carry higher mortality (5–6% vs. 2–3% in enriched cages), injurious pecking, and disease risks requiring careful management to translate structural improvements into genuine welfare gains (Lay *et al.*, 2011; <https://doi.org/10.3382/ps.2011-01780>)^[26].

8. Challenges in Technology Adoption

8.1 The Technology Adoption Gap

Technologies reviewed in this paper are predominantly developed for intensive, capitalized, high-labor-cost production systems in Europe, North America, and Australasia. Their relevance and accessibility for 600 million smallholder livestock keepers in LMICs typically keeping 1–5 cattle or 10–50 poultry with minimal cash income is

fundamentally limited (Herrero *et al.*, 2010; <https://doi.org/10.1016/j.livscipro.2009.11.049>)^[17].

Technology transfer requires: co-development with farming communities; adaptation to local breeds, disease environments, and feed resources; affordable delivery mechanisms; gender-sensitive extension; and enabling policy environments. Mobile platform delivery (Digital Green's video advisory in India; iCow SMS services in Kenya) demonstrates viable alternative channels for reaching resource-limited producers.

8.2 Economic, Regulatory, and Data Governance Barriers

Milking robots (€80,000–200,000/unit; 7–12-year payback under favorable conditions), high-density SNP arrays (€50–150/animal), and comprehensive herd health platforms require capital access unavailable to most global producers. Technology-as-a-service business models and cooperative purchasing arrangements partially address this. Regulatory fragmentation for gene-edited livestock (streamlined UK pathway vs. full EU GMO assessment vs. FDA animal drug regulation in the USA) creates market uncertainty deterring innovation investment. Farm data governance data ownership, interoperability, and secondary use protections where large technology companies capture value from farmer-generated sensor data remains legally and contractually underspecified, threatening farmer trust and adoption (Jakku *et al.*, 2019; <https://doi.org/10.1016/j.njas.2019.01.008>)^[23]. Rural broadband infrastructure deficits bind PLF adoption across Sub-Saharan Africa, South Asia, and parts of Latin America.

9. Future Prospects

9.1 Cellular Agriculture: Cultivated meat proliferating animal myosatellite cells in bioreactors without slaughter received its first commercial approvals in Singapore (2020) and the USA (2023). Production costs have declined from USD 325,000/burger (2013) to an estimated USD 10–20/kg for chicken (2024), though commercial parity with conventional chicken (~USD 2–3/kg) requires further bioreactor scale-up, serum-free media development, and scaffold engineering breakthroughs (Tuomisto *et al.*, 2014; <https://doi.org/10.1371/journal.pone.0101897>)^[52]. Precision fermentation producing animal-identical proteins (casein, whey, egg albumin, heme) via microbial hosts offers potentially faster commercial routes and is advancing through regulatory review in multiple jurisdictions.

9.2 Multi-omics, Climate Adaptation, and One Health

Multi-omics integration (genomics, transcriptomics, metabolomics, microbiomics) combined with high-throughput PLF phenotyping is enabling genomic selection for traits historically unmeasurable at population scale feed efficiency, behavioral welfare indicators, and immune competence (Bouwman *et al.*, 2018; <https://doi.org/10.1038/nbt.4143>)^[4]. IPCC Sixth Assessment Report projections (2022; <https://doi.org/10.1017/9781009157940>) indicate that without aggressive mitigation, >2°C warming by 2050 will significantly expand heat stress zones, alter disease distributions, and degrade rangeland productivity; genomic selection and gene editing for heat tolerance, drought-adapted forage varieties, and silvopastoral system expansion are priority adaptations. The COVID-19 pandemic, H5N1 HPAI's unprecedented spread into dairy cattle (USA, 2024), ASF's global devastation, and AMR's trajectory collectively make the One Health integration of human, animal, and ecosystem health surveillance sharing data platforms, analytical capacity,

and response infrastructure an urgent governance priority (Zinsstag *et al.*, 2011; [https://doi.org/10.1016/S0140-6736\(11\)60959-3](https://doi.org/10.1016/S0140-6736(11)60959-3))^[59].

10. Conclusion

This review documents an extraordinary breadth and pace of technological innovation transforming livestock production. Genomic selection, CRISPR editing, PLF sensor networks, AI-driven decision support, methane-mitigating additives, next-generation vaccines, and integrated One Health surveillance collectively constitute a technological capability set capable of delivering livestock systems that are simultaneously more productive, more efficient, more sustainable, and more humane. These are not distant prospects many are commercially deployed today.

Yet the distribution of benefits is profoundly uneven. Technologies designed for intensive, capitalized production systems risk consolidating advantages within already-privileged operations while marginalizing the 600 million smallholder farmers on whom global food security disproportionately depends. Environmental sustainability must be embedded as a co-equal primary objective, not treated as a constraint. Regulatory frameworks for gene editing require urgent international harmonization. The social and governance dimensions of technology transition equity, access, data rights, cultural compatibility require as much investment as the biological and digital science.

Research priorities include: genomic improvement programs for locally adapted breeds in LMICs; low-cost PLF tools for smallholder deployment; rigorous welfare and environmental impact evaluations of emerging housing transitions; harmonized regulatory frameworks for precision breeding; and strengthened One Health surveillance infrastructure. The livestock production sector of 2050 will be defined by decisions made today. Whether the outcome serves the full spectrum of human and animal needs across income levels, geographies, and species will depend on the equity, wisdom, and foresight with which these innovations are governed and shared.

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